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MISSILE DATCOM: HIGH ANGLE OF ATTACK CAPABILITIES

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ABSTRACT

Missile Datcom is a computer program for estimating the aerodynamic stability and control characteristics of missile configurations. The code is in use in the aerospace community and has been successfully used for conceptual and preliminary design activities. There is renewed interest in high angle-of-attack missile capability, fueled by the need for rapid maneuvers immediately after missile launch to track high off boresight targets. The capabilities and limitations of Missile Datcom in this area are discussed. Comparisons of Missile Datcom results with high angle-of-attack wind tunnel data are made. Only longitudinal (pitch plane) cases are analyzed.

NOMENCLATURE

C_A	Axial Force Coefficient
$C_{A,o}$	Axial Force Coefficient at zero lift
$C_{A,\alpha}$	Axial Force Coefficient due to lift
$C_{A,blunt}$	Axial Force Coefficient of truncated nose
C_L	Lift Coefficient
C_m	Pitching Moment Coefficient
C_N	Normal Force Coefficient
$C_{N\alpha}$	Normal Force Slope
$C_{N\alpha\alpha}$	Non-linear Normal Force Slope
$C_{N,B}$	Body Normal Force Coefficient
$C_{N,F}$	Fin Normal Force Coefficient
$C_{N,p}$	Potential Normal Force Coefficient
$C_{N,v}$	Viscous Normal Force Coefficient
x_{ac}	Longitudinal Location of Aerodynamic Center
x_{cg}	Longitudinal Location of Center of Gravity
α	Angle of Attack
α_{eq}	Equivalent Angle of Attack
δ	Fin Deflection Angle
ϕ	Roll Angle

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INTRODUCTION

Missile Datcom is an engineering level computer code for estimating the aerodynamic stability and control characteristics of missile configurations [Ref. 1]. Missile Datcom can provide estimates for axisymmetric and elliptic bodies with up to four finsets. Each finset may contain up to 8 fins with arbitrary roll and dihedral angles. Missile Datcom can also model air breathing inlets and protuberances. The code is extremely robust and there are no hard limits imposed on angle-of-attack. Missile Datcom will provide output for all angles-of-attack. The purpose of this paper is to discuss the methods used and to examine the validity of the Missile Datcom predictions at high angle-of-attack. There has been a renewed interest in high angle-of-attack missile aerodynamic stability and control [Ref. 2] The high angle of attack capabilities of other engineering prediction codes, the Navy AP98 [Ref. 3] and Nielson Engineering & Research's M3HAX [Ref. 4], have previously been presented.

PREDICTION METHODOLOGY

Missile Datcom uses the component build-up method for predicting aerodynamics. Separate predictions are made for the isolated body and fins. These are then summed using appropriate interference factors to determine the overall forces and moments. These calculations will be discussed in separate sub-sections, with an emphasis on the relations used at very high angle of attack.

BODY ALONE

Missile Datcom uses the Allen and Perkins [Ref. 5] viscous crossflow method for normal force and center of pressure of bodies at high angles of attack. This method divides the incremental force acting along the body into separate potential flow and viscous flow increments. These are linearly summed to give the overall force. Jorgensen [Ref. 6] extended the method to non-circular cross-sections by correcting these increments. The potential flow increment is corrected using slender body theory, the viscous flow increment is corrected using Newtonian flow theory. The equations used in the code are:

$$C_N = \frac{C_{N\alpha}}{2}\sin 2\alpha \cos(\alpha/2)\left(\frac{C_n}{C_{no}}\right)_{SB} + \eta C_{Dc}\sin\alpha\left|\sin\alpha\right|\frac{S_p}{S}\left(\frac{C_n}{C_{no}}\right)_{Newt} \quad \textbf{(1)}$$

$$C_m = \frac{C_{N\alpha}}{2}\left(\frac{x_{cp}-x_{cg}}{l}\right)\sin 2\alpha' \cos(\alpha'/2)\left(\frac{C_n}{C_{no}}\right)_{SB} + \eta C_{Dc}\sin\alpha\left|\sin\alpha\right|\frac{S_p}{S}\left(\frac{x_c-x_{cg}}{l}\right)\left(\frac{C_n}{C_{no}}\right)_{Newt} \quad \textbf{(2)}$$

$$\alpha' = \alpha \quad for \quad -90 < \alpha < 90$$

$$\alpha' = \alpha - 180 \quad for \quad 90 < \alpha < 180$$

The absolute value terms ensure the correct sign at negative angles of attack. At high angles of attack, the crossflow drag coefficient (C_{Dc}) is the single most important factor in these equations. A comparison of the crossflow drag values used by Missile Datcom and two other popular engineering prediction codes, the Navy AP98 and Nielsen Engineering & Research M3HAX, is shown in Figure 1.

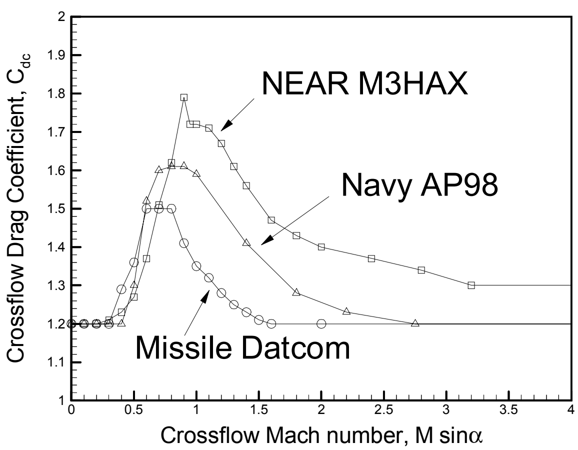

Figure1: Comparison of Crossflow Drag Correlations

The bulk of the difference in body alone predictions generated by these codes can be traced to the differences shown in this figure. The major differences occur in the region of transonic crossflow. The highest crossflow drag values are used by M3HAX, which uses the data correlation developed by Jorgensen [Ref. 6]. Missile Datcom uses a modified version of Baker's [Ref 15] correlation, which gives the lowest crossflow drag values. AP98 includes more recent data in its correlation, and gives values in between the other codes. AP98 also includes a correction for the portions of the body that include lifting surfaces, since the primary crossflow drag data sets are for body alone configurations. Missile Datcom assumes a constant value of the crossflow drag over the entire vehicle. If the body has mixed laminar and turbulent flow, a more accurate implementation would be to allow the crossflow drag to vary along the body length. This is the approach taken in the AP98 code. The center of pressure of the body at large angles of attack is effectively at the planform centroid.

At smaller angles of attack, the potential normal force slope ($C_{N\alpha}$) and center of pressure in Missile Datcom are determined from empirical charts or slender body theory below Mach 1.2. At low supersonic Mach numbers, Van Dyke Hybrid Theory is used for bodies with pointed noses. For bodies with blunt noses or at higher supersonic Mach numbers (roughly M>3), Second Order Shock Expansion is used. At very high Mach numbers, Modified Newtonian theory is available as a code option.

Axial force is computed by:

$$C_A = C_{A,o} + C_{A,\alpha} \qquad 0 < \alpha < 30$$

$$C_A = C_{A,o}\cos^2\alpha \qquad 30 < \alpha < 90 \qquad \textbf{(3)}$$

$$C_A = -C_{A,blunt} \qquad 90 < \alpha < 180$$

The skin friction, pressure, and base drag are assumed to be independent of angle of attack. The wave drag and lift induced drag terms are computed as a function of angle of attack. Below 30^o angle of attack, lift induced drag is assumed to be equal to $C_L\sin(\alpha)$. The lift coefficient is computed from the normal force and zero angle of attack axial force as follows:

$$C_L = \frac{C_N - C_{A,o}\sin\alpha}{\cos\alpha + \sin^2\alpha} \qquad \textbf{(4)}$$

Above 30^o, the Jorgensen axial force approximation [Ref. 6] is used. His correction is based on the reduction in dynamic pressure along the body.

The 5/97 revision to Missile Datcom includes two changes in the C_A calculation at high angles of attack. The angle of attack for switching to the Jorgensen approximation was reduced from 45^o to 30^o to minimize the discontinuity as the method switches. At angles of attack greater than 90^o, the blunt base becomes forward facing, contributing a large negative axial force. An empirical data table from Hoerner [Ref. 7] is used to calculate this increment.

FIN ALONE

The normal force and pitching moment of a fin are determined using the methods of the USAF Datcom handbook [Ref. 8]. Normal force is computed in a manner similar to the viscous crossflow method:

$$C_N = \frac{C_{N\alpha}}{2}\sin 2\alpha + C_{N\alpha\alpha}\sin\alpha\left|\sin\alpha\right| \quad \textbf{(5)}$$

The nonlinear term $C_{N\alpha\alpha}$ is the dominant term at large angles of attack. At very high angles of attack it is analogous to the crossflow drag coefficient. It varies with angle of attack, fin planform, and airfoil section characteristics. It is computed as a function of the maximum lift and angle of attack for maximum lift of the fin. The maximum lift terms are computed using the empirical methods within the USAF Datcom handbook. The normal force slope ($C_{N\alpha}$) is also computed from the Datcom handbook.

Fin pitching moment is computed from the potential and viscous terms of equation (5) as follows:

$$C_m = \frac{(x_{ac} - x_{cg})C_{N,p}}{l} + \frac{(x_c - x_{cg})C_{N,v}}{l} \quad \textbf{(6)}$$

The potential normal force is assumed to act at the fin aerodynamic center, which is obtained from charts from the USAF Datcom for aft-swept fins and from charts from Sharpes [Ref. 9] for forward swept fins. The viscous normal force is assumed to act at the panel centroid.

Axial force is computed from:

$$C_A = C_{A,o} + C_{A,\alpha} \quad \textbf{(7)}$$

The skin friction, pressure, wave, and base drag are assumed to be independent of angle of attack. The axial force due to angle of attack term is computed from induced drag relationships for wings. At subsonic speeds for fins with rounded leading edges, induced drag is assumed to be equal to $K_v C_L^2$. The K_v term is computed from the USAF Datcom handbook. Fin lift is computed from normal force and axial force at zero angle of attack:

$$C_L = \frac{1}{2K_v \tan\alpha}\left(-1 + \sqrt{1 + \frac{4K_v \tan\alpha}{\frac{C_N}{\cos\alpha} - C_{A,o}\tan\alpha}}\right) \quad \textbf{(8)}$$

At supersonic speeds or for fins with sharp leading edges, induced drag is assumed to be equal to the $C_L \tan(\alpha)$, which gives $C_A(\alpha)=0$.

BODY-FIN INTERFERENCE

Missile Datcom uses the "equivalent angle of attack" method developed by Hemsch and Nielsen [Ref. 10] to compute the fin-body interference effects. This concept assumes the factors which contribute to the normal force on a fin (angle of attack, bank angle, body upwash, deflection and vortex effects) can be expressed as increments in angle of attack and can be linearly summed to give an equivalent total angle of attack. The normal force curve for the isolated fin is interpolated at the equivalent angle of attack to give the force on the fin in the actual flowfield. This procedure gives:

$$C_N = C_{N,B} + \sum_{sets}\left(1 + \frac{K_{B(W)}}{K_{W(B)}}\right)\sum_{fins} C_{N,F}\Big|_{\alpha,eq} \quad \textbf{(9a)}$$

where:

$$\alpha_{eq} = \alpha_{eq}\Big|_{\delta=0} + \sum_{fins}\Lambda_{ji}\delta_i \quad \textbf{(9b)}$$

$$\tan\alpha_{eq}\Big|_{\delta=0} = K_W \sin\phi\tan\alpha - K_\phi \tan\Lambda\sin\alpha\tan\alpha\sin\phi\cos\phi + \tan\Delta\alpha_{vor} \quad \textbf{(9c)}$$

The terms included in this analysis have been expanded in Missile Datcom to give the effects of fin dihedral (for folding fins) and steady rotation (for dynamic derivatives).

The "K" factors in equations (9a,9c) are taken from slender body theory with the exception of Kw. This term has been extracted from wind tunnel tests [Ref. 11], which found a definite angle of attack effect. The upwash is slightly larger at zero angle of attack than predicted by slender body theory. This increase is a function of the body diameter to span ratio. As angle of attack increases, the upwash decreases to the slender body value and continues towards unity at the highest angles of attack. The point where the upwash is equal to the slender body is a function of the Mach number. The following empirical expressions, developed by Burns and Bruns [Ref. 11], capture these trends:

$$K_W = 1 + \left(K_{W(SBT)} + \delta - 1\right)e^{-B\left|\alpha^{1.5}\right|} \quad \textbf{(10)}$$

where:

$$\delta = K_W(0) - K_{W(SBT)}$$

$$B = \frac{1}{\left|\alpha_{SBT}{}^{1.5}\right|}\ln\left(1 + \frac{\delta}{K_{W(SBT)} - 1}\right) \quad \textbf{(11a,b)}$$

The empirically determined factors are $K_W(0)$ (upwash at zero angle of attack) and α_{SBT} (angle of attack where upwash equals slender body theory value).

MODIFICATIONS TO 5/97 REVISION

One new capability was added to the code during this investigation. The 5/97 and prior revisions of Missile Datcom required a minimum longitudinal spacing between finsets to prevent errors (or code failure) in the vortex tracking algorithm. Many configurations have fins of dissimilar planform at the same axial location. Examples are cruise missiles with "vertical" and "horizontal" tails and airbreathing configurations with some fins mounted on the inlets and others on the body. The code was modified to skip the vortex tracking calculation between two fin sets if the leading edge of a fin in the aft set is ahead of the trailing edge of a fin in the forward set. The data comparison in Figure 2 illustrates the effect of this change. The configuration shown in Figure 2 [Ref. 12] had tailfins of differing planforms. Previous versions of Missile Datcom would require that the fin geometry be input as three fins of the same planform. The new code allows for overlapping finsets, so the actual fin planforms can be modeled. The result is a more realistic physical geometry input and a better match with test data.

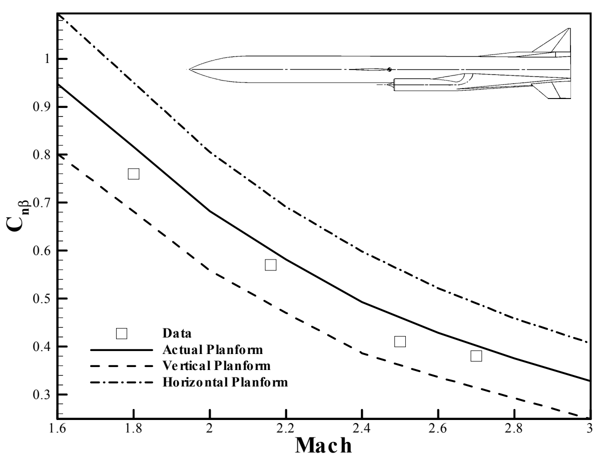

Figure 2: Overlapping Finset Comparison

Several changes were made to the 5/97 revision of Missile Datcom to correct errors which were uncovered while investigating high angle of attack predictions.

The Jorgensen method [Ref. 6] for pitching moment of a body has a different form for the potential flow contribution for angles of attack above and below 90^o. This is reflected by the α' term in eq. (2). This was improperly implemented in the 5/97 and prior versions of the code, leading to a kink in the predictions at 90^o angle of attack.

The "equivalent angle of attack" of an undeflected fin, as published in [Ref. 10] and originally implemented in Missile Datcom is shown below.

$$\tan\alpha_{eq} = K_W \sin\phi\tan\alpha - K_\phi \tan\Lambda\sin\alpha\tan\alpha\sin\phi\cos\phi \qquad \textbf{(12)}$$

The algebraic sign of the tan α term changes above 90^o and below –90^o. This causes an error in the calculated equivalent angle of attack when the FORTRAN arc-tangent function is used. The implementation of the equivalent angle of attack method was changed to the following:

$$\tan\alpha_{eq} = K_W \sin\phi\sin\alpha/|\cos\alpha| - K_\phi \tan\Lambda\sin^2\alpha\sin\phi\cos\phi/|\cos\alpha| \qquad \textbf{(13)}$$

The original (11/85) release of Missile Datcom was not applicable to high aspect ratio fins (AR>3) in the high angle of attack regime. The USAF Datcom handbook method [Ref. 8] for high aspect ratio fins (AR>4) was later incorporated into the code. For these fins, a mistake was uncovered in the maximum lift coefficient calculation for fins with small leading edge radii or thickness ratios. This led to an error in the nonlinear normal force calculation ($C_{N\alpha\alpha}$, eq. 5) which resulted in significant underprediction of normal force.

When a fin is deflected, the pressure field it generates causes loads on adjacent fins. These loads act in a direction that opposes the rolling moment caused by the deflected fin. This effect is included in the equivalent angle of attack method through the terms Λ_{ij} in eq. 9b. These terms are obtained from slender body theory. At supersonic speeds, the zone of influence on adjacent fins is reduced if the Mach lines from the deflected pass through the adjacent fin. This reduction was not included in the 5/97 and prior revisions of the code, although most of the appropriate code was present. This led to large underpredictions of rolling moments at supersonic speeds. The code was modified to correctly implement this effect.

Errors were also found and corrected in the following calculations: pitching moment increment due to vertical center of gravity offset for body alone cases; wave drag for airfoil sections with thickness to chord ratios less than 1%; body alone skin friction drag calculation at exactly 90^o angle of attack.

DATA COMPARISONS

AIR SLEW

The Air Slew configuration consists of a simple tangent ogive nose-cylindrical body with a single set of 4 fins. A sketch is shown in Figure 3. This configuration was tested extensively in the mid 1970s and test data are available from 20^o to 180^o angle of attack [Ref 13]. Comparisons between Missile Datcom predictions and test data for the complete configuration are shown in Figures 4 through 6.

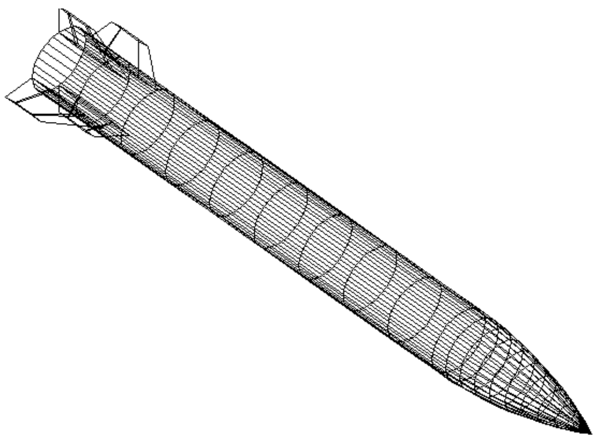

Figure 3: Air Slew Configuration Sketch

The normal force comparison is shown in Figure 4. Both versions of Missile Datcom predict normal force very well at M=1.51 for angles of attack below 90^o. Missile Datcom underpredicts the normal force at M=2.0 for angles of attack below 90^o.

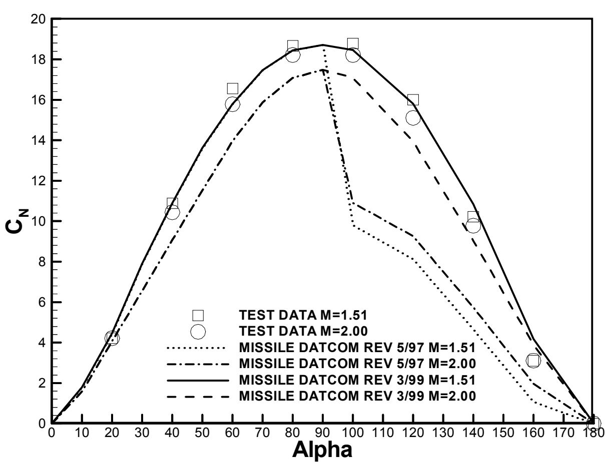

Figure 4: Air Slew Normal Force Comparison

The normal force predictions from the 5/97 Revision of Missile Datcom exhibit a step change at 90^o angle of attack. This is due to the errors discussed above. The revised version of the code (Rev. 3/99) shows vastly improved normal force predictions for angles of attack above 90^o.

The X_{cp} comparison is shown in Figure 5. Both versions of the code do a good job of predicting the center of pressure location at angles of attack below 90^o. The center of pressure location prediction shows a large change at 90^o angle of attack when using the 5/97 Revision of Missile Datcom. The changes to the code show an improvement in the center of pressure prediction at angles of attack above 90^o. The revised code (Rev. 3/99) captures the aft movement of the center of pressure at angles of attack above 140^o.

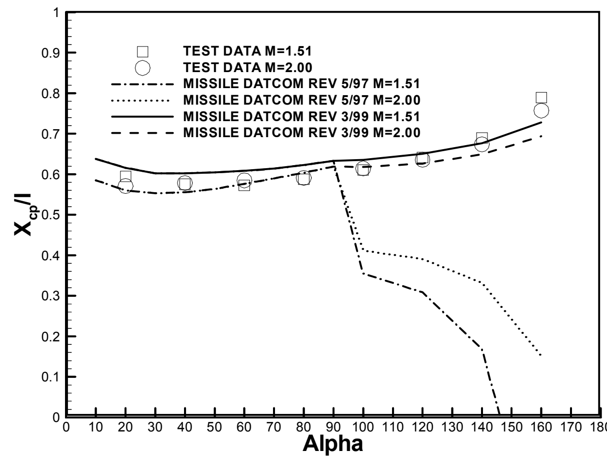

Figure 5: Air Slew Center of Pressure Comparison

The axial force comparison is shown in Figure 6. Missile Datcom predicts the general trend with angle of attack, but underpredicts the magnitudes below 90^o angle of attack and overpredicts above 90^o. The changes made to Missile Datcom do not affect the axial force prediction.

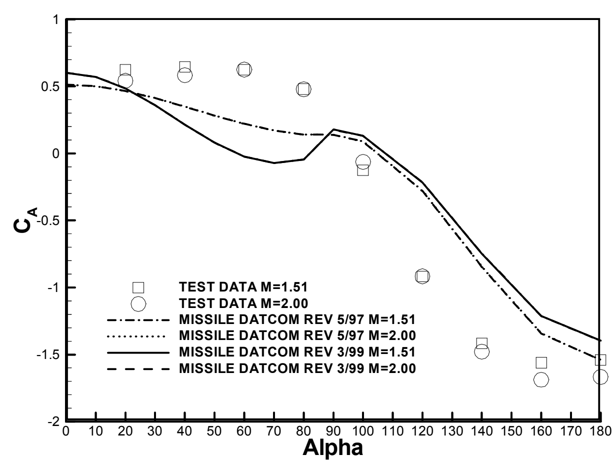

Figure 6: Air Slew Axial Force Comparison

AIM-95 "AGILE"

The AIM-95 "AGILE" configuration consists of a hemispherical nose cap, a short cylindrical section and a flare followed by a cylindrical body. A single finset composed of 8 fins is near the aft end of the body. The AGILE configuration was tested in the early 1970s and test data is available at angles of attack up to 90^{o} [Ref. 14]. A sketch of the model is shown in Figure 7. Test data at Mach Numbers of 0.6, 1.1, 1.6, and 2.0 are available for this configuration. Both body alone and body+fins data is available for normal force and pitching moment. No axial force data was available.

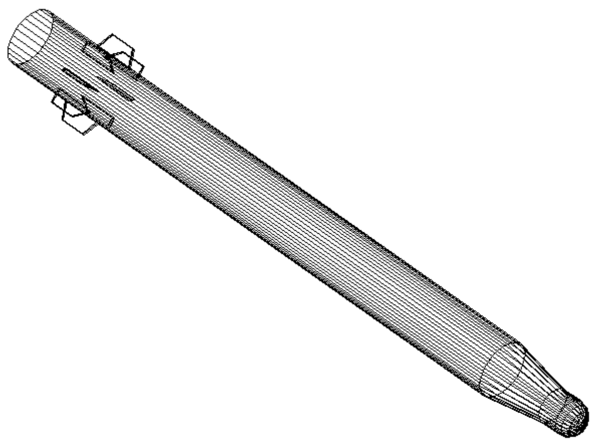

Figure 7: AGILE Missile Configuration

The body alone normal force and X_{cp}/l are shown in Figures 8 through 11. The Missile Datcom C_N predictions show very good agreement with the test data through 70^{o} angle of attack for the lower Mach number cases and through 60^{o} for the higher two Mach numbers. Above 70^{o} angle of attack, the test data shows an increase in normal force slope at Mach numbers of 0.8 and 1.1. Figures 10 and 11 show a comparison between predicted and test values for X_{cp}/l. The Missile Datcom predictions show very good agreement at Mach numbers of 1.6 and 2.0 throughout the angle of attack range. At the lower two Mach numbers, the Missile Datcom prediction does not capture a pitch-up in the body alone case at angles of attack between 30^{o} and 70^{o}. This pitch-up tendency has been seen by other researchers, and an empirical method was developed to help predict this tendency by Baker [Ref 15]. This method has not been included in Missile Datcom.

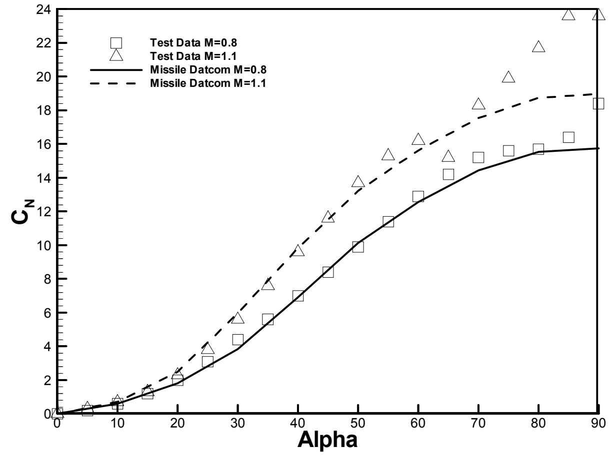

Figure 8: Body Alone Normal Force Comparison, M=0.8, 1.1

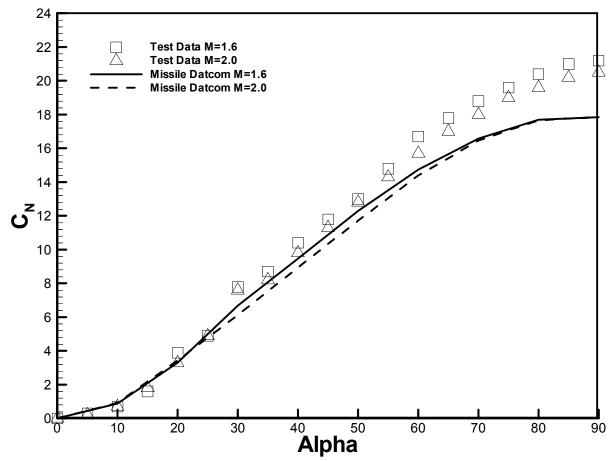

Figure 9: Body Alone Normal Force Comparison, M=1.6, 2.0

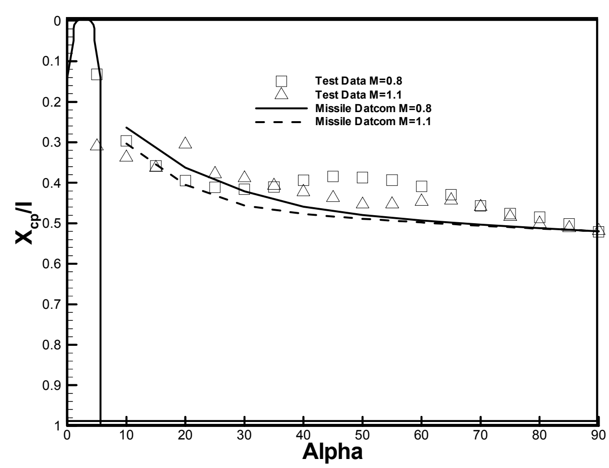

Figure 10: Body Alone Center of Pressure Comparison, M=0.8, 1.1

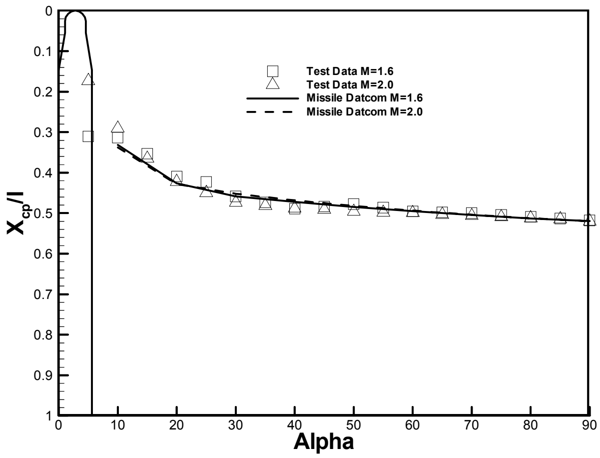

Figure 11: Body Alone Center of Pressure Comparison, M=1.6, 2.0

Figures 12 through 15 contain comparisons between the test data and Missile Datcom predictions for the complete configuration. The Missile Datcom C_N predictions show very good agreement with the experimental data through most of the angle of attack range. Missile Datcom overpredicts the normal force above 60^o angle of attack for the subsonic case. The center of pressure location is not as well predicted, especially for the two lower Mach numbers. This again occurs between 30^o and 70^o angle of attack and can mainly be attributed to the body alone pitch-up that was seen in the experimental data. As was noted above, an empirical method was developed by Baker [Ref 15] to account for this pitch-up tendency. A review of this method may be made to see if it can be incorporated into Missile Datcom. The center of pressure location was adequately predicted for the preliminary design purposes at the higher Mach numbers.

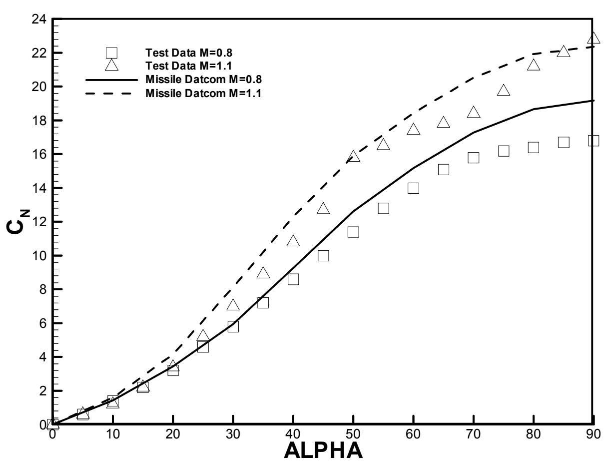

Figure 12: Full Configuration Normal Force Comparison, M=0.8, 1.1

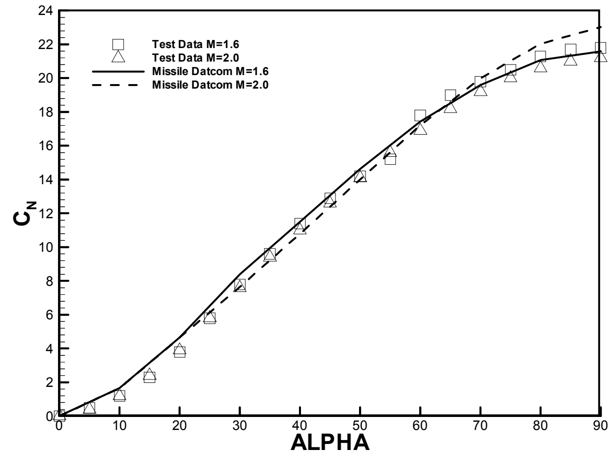

Figure 13: Full Configuration Normal Force Comparison, M=1.6, 2.0

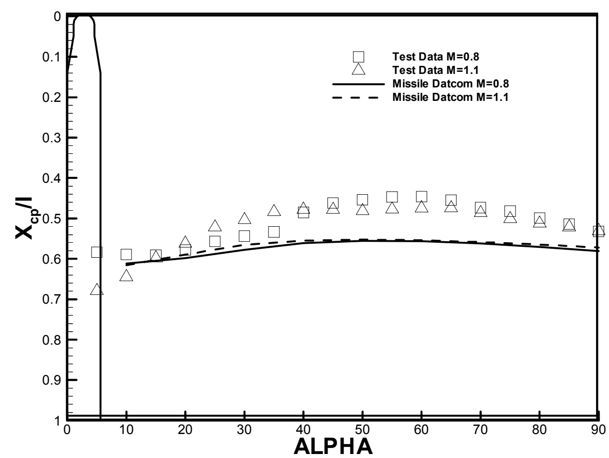

Figure 14: Full Configuration Center of Pressure Comparison, M=0.8, 1.1

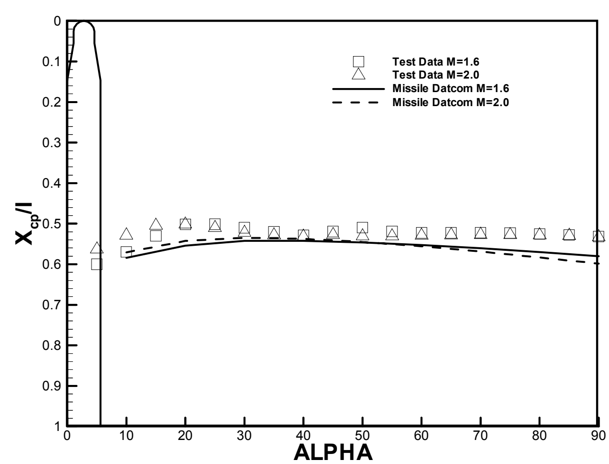

Figure 15: Full Configuration Center of Pressure Comparison, M=1.6, 2.0

MARTIN GENERALIZED RESEARCH MODEL

The Martin Generalized Research Model [Ref. 16] was tested with varying tail fin planforms and fin deflection angles. Missile Datcom was used to generate predictions for the effects of fin deflection for two fin planforms. Sketches of the configuration and fins are shown in Figs 16-18.

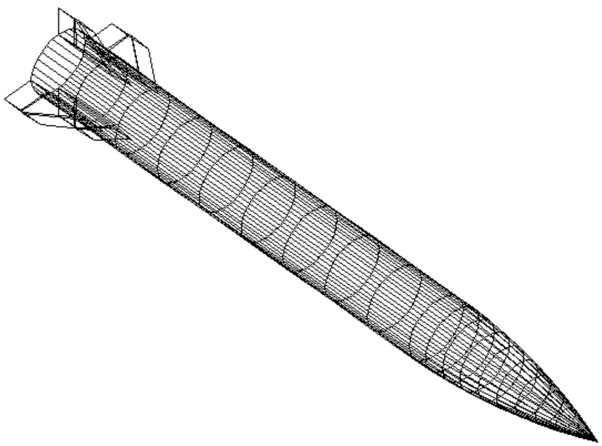

Figure 16: Martin Generalized Research Model

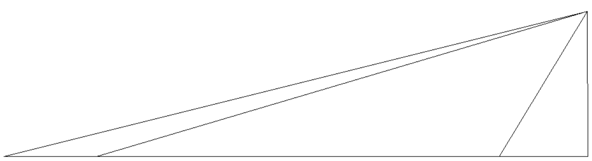

Figure 17: Fin 14

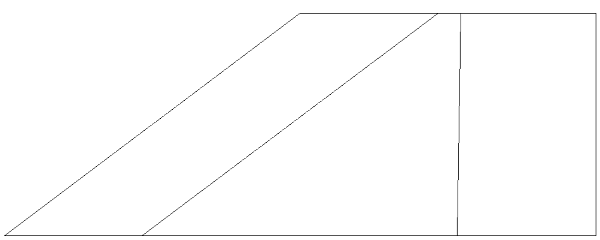

Figure 18: Fin 15

This configuration was tested at angles of attack between –5^o and 60^o at Mach numbers varying from 0.8 to 1.1. The tail fins were oriented in the “plus” configuration and the horizontal fins were deflected symmetrically (i.e. pitch deflections).

Missile Datcom data comparisons for the Mach=0.8 case are contained in Figures 19 through 22. Missile Datcom slightly overpredicts the normal force due to deflection for both fin planforms for angles of attack below 50^o. The Missile Datcom pitching moment predictions show excellent agreement with the test data at angles of attack below 30^o. Above 30^o angle of attack, the test data shows a break in the pitching moment curve that Missile Datcom does not predict.

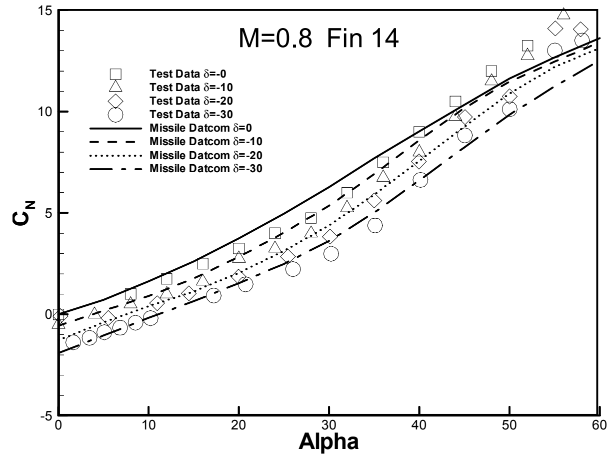

Figure 19: Normal Force Comparison, Fin 14, M=0.8

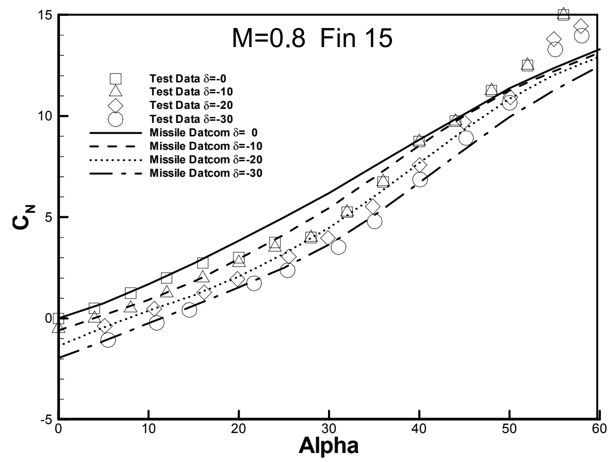

Figure 20: Normal Force Comparison, Fin 15, M=0.8

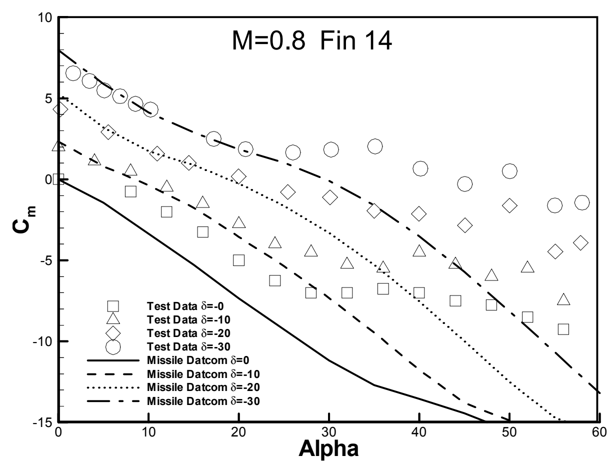

Figure 21: Pitching Moment Comparison, Fin 14, M=0.8

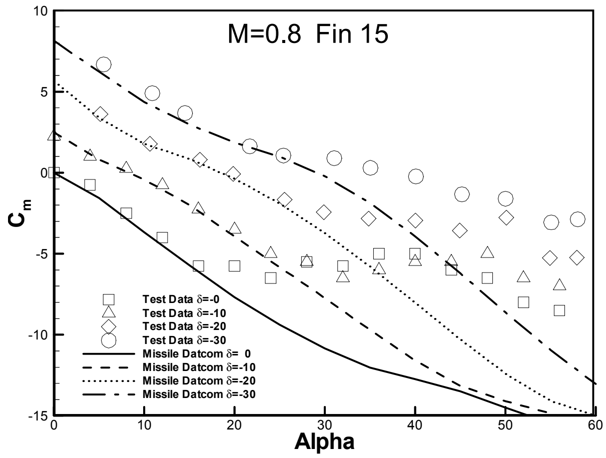

Figure 22: Pitching Moment Comparison, Fin 15, M=0.8

Missile Datcom data comparisons for the Mach=1.1 case are shown in Figures 23 through 26. The normal force predictions show excellent agreement with the test data for both fin planforms.

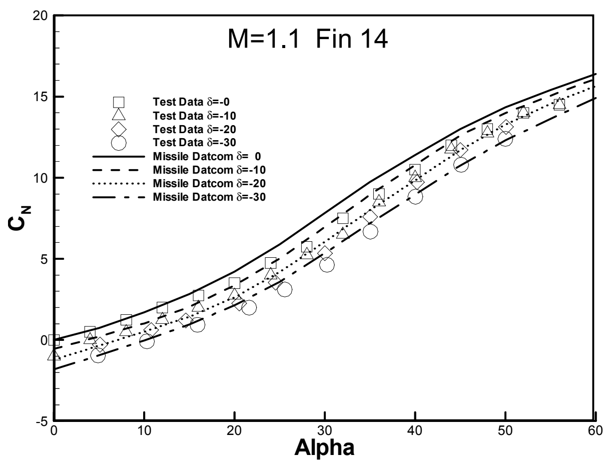

Figure 23: Normal Force comparison, Fin 14, M=1.1

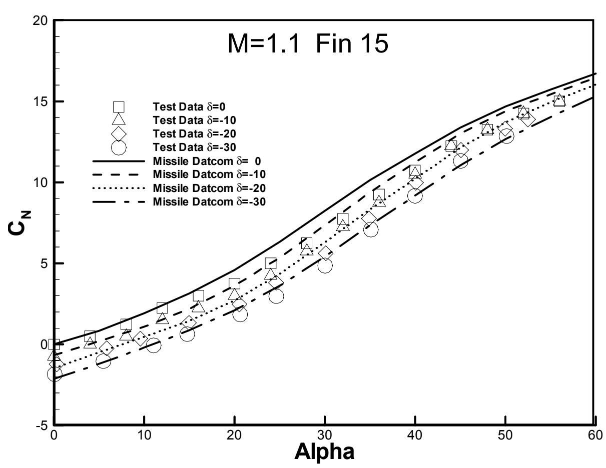

Figure 24: Normal Force comparisonc Fin 15, M=1.1

As with the subsonic case, the pitching moment predictions show good agreement with test data at lower angles of attack. At this low supersonic Mach number, the test data shows a pitching moment break at approximately 20^o or 25^o angle of attack. Missile Datcom does not capture this pitching moment break.

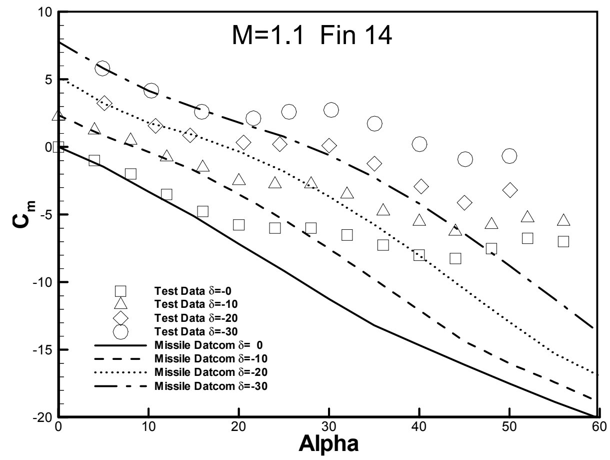

Figure 25: Pitching Moment comparison Fin 14, M=1.1

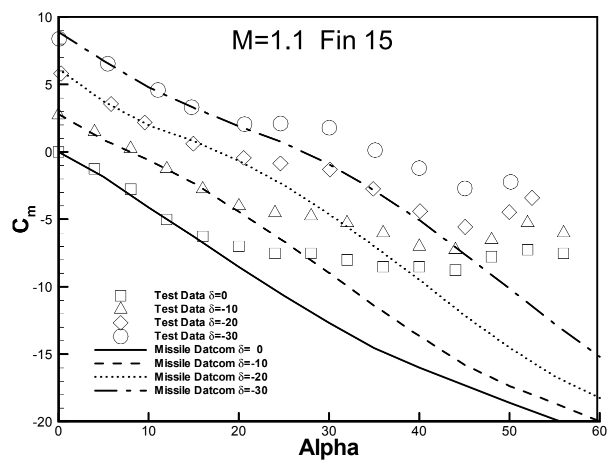

Figure 26: Pitching Moment comparison, Fin 15, M=1.1

Missile Datcom adequately predicted the normal force characteristics of this configuration throughout the angle of attack range and fin deflections considered. The pitching moment predictions showed very good agreement at low angles of attack; however, this configuration exhibited a break in the pitching moment curve at angles of attack above 30^o that was not predicted by Missile Datcom.

CONCLUSIONS

A study of Missile Datcom predictions in the high angle of attack region was conducted. The 5/97 version of the code was used as the baseline. During the course of the investigation, several errors in the code were found that dramatically affected the high angle of attack predictions, especially for angles of attack exceeding 90°.

The modified code was compared with wind tunnel data for three configurations. Comparisons were made for both body alone and complete configurations at transonic and supersonic speeds. Only longitudinal (pitch plane) cases were analyzed. Overall, normal force and axial force were well predicted and adequate for preliminary design calculations. The accuracy of the center of pressure (or pitching moment) predictions varied with Mach number. At transonic speeds, predictions were good up to about 30°. Above that, a pitch up tendency due to the body existed that was not well predicted by the Jorgensen method used in Missile Datcom. An empirical method to account for this effect was developed by Baker, and may be incorporated into a future version of the code. At supersonic speeds, center or pressure was well predicted at all angles of attack. Increments due to fin deflection were adequately predicted, but total pitching moment values were not, due to the failure to predict body pitch up noted above.

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REFERENCES

1. Blake, W.B., "Missile Datcom User's Manual – 1997 Fortran 90 Revision," AFRL-VA-WP-TR-3009, February 1998.

2. "USAF To Work On New Missile Control Technology," Aerospace Daily, December 22, 1998, McGraw-Hill.

3. Moore, F.G., "The 1998 Version of the NSWC Aeroprediction Code: Part I – Summary of New Theoretical Methodology," NSWCDD/TR-98/1, April 1998.

4. Lesieutre, D.J., Love, J.F., and Dillenius, M.F.E., "M3HAX – Aerodynamic Analysis for Finned Vehicles with Axisymmetric Bodies," NEAR TR 493-D, February 1996.

5. Allen, H.J., and Perkins, E.W., "A Study of the Effects of Viscosity on Flow Over Slender Inclined Bodies of Revolution," NACA TR 1048, 1951.

6. Jorgensen, L.H., "Prediction of Static Aerodynamic Characteristics for Slender Bodies Alone and with Lifting Surfaces to Very High Angles of Attack," NASA TR-R-474, September 1977.

7. Hoerner, S.F., "Fluid Dynamic Drag," published by the author, 1965.

8. Hoak, D.E., et al, "The USAF Stability and Control Datcom," AFWAL TR-84-3084, April 1960 (revised 1978).

9. Sharpes, D.G., "Validation of the USAF Datcom Methodologies for Straight-Tapered Forward Swept Wings," AFWAL TR 84-3084, July 1985.

10. Hemsch, M.J., and Nielsen, J.N., "Equivalent Angle of Attack Concept for Estimating Nonlinear Aerodynamics of Missile Fins," Journal of Spacecraft and Rockets, July-August 1983, pp. 356-362.

11. Burns, K.A., and Bruns, K.D., "Development of an Improved Carryover Interference Method for Missile Datcom," AIAA paper 96-3395, July 1996.

12. Hayes, C., and Sawyer, W.C., "Aerodynamic Characteristics of a Series of Air-Breathing Missile Configurations Investigated as Part of the SASS Program," NASA TM 80139, December 1979.

13. Hahn, J.S., "Static Stability Tests of the Air Slew Demonstrator Missile at Mach Numbers 1.5 and 2 and Angles of Attack From 30 to 180 Deg," AEDC-TR-76-83, June 1976.

14. Heiberger, F.S., "AGILE External Geometry Test," MDC G4027, June 1973.

15. Baker, W.B.Jr, "An Aerodynamic Coefficient Prediction Technique for Slender Bodies with Low Aspect Ratio Fins at Mach Numbers From 0.6 to 3.0 and Angles of Attack From 0 to 180 Degrees," AEDC-TR-77-97, March 1978.

16. Gomillion,G.R., "A Compilation of Static Stability and Fin Loads for Slender Body Missile Models with and without Tail Fins and Wings – Volume V," AEDC-TR-75-125, March 1976.